

ACCURATE REALIZATION OF GPS VERTICAL GLOBAL REFERENCE FRAME

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Annual Report #2

For the Period 1 October 2004 through 30 September 2005

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1- Research Context

The goal of this project is to improve our current understanding of GPS error sources associated with estimates of radial velocities at global scales. An improvement in the accuracy of radial global velocities would have a very positive impact on a large number of geophysical studies of current general interest such as global sea-level and climate change, coastal hazards, glacial isostatic adjustment, atmospheric and oceanic loading, glaciology and ice mass variability, tectonic deformation and volcanic inflation, and geoid variability. A set of GPS error sources relevant to this project are those related to the combination of the positions and velocities of a set of globally distributed stations as determined from the analysis of GPS data, including possible methods of combining and defining terrestrial reference frames. This is where our research activities during this reporting period have concentrated.

2- Research Activities

During this reporting period, we have researched two topics:

- The effect of errors on the GPS satellite antenna models (or lack thereof) on global GPS vertical position and velocity estimates;
- The effect of reference frame definition and practice on estimates of the geocenter variations.

3- Research Results

The following list includes publications and presentations of results directly related to this grant:

- Elosegui, P., J.L. Davis, M.E. Tamisiea, J.X. Mitrovica, Estimating Geocenter Variations by Combining GRACE and GPS data sets, (in preparation; Addendum), Geo. Res. Lett., 2005.
- Davis, J.L., P. Elosegui, J.X. Mitrovica, M.E. Tamisiea, Climate-Driven Deformation of the Solid Earth from GRACE and GPS, Geophys. Res. Lett., 31, L24605, doi:10.1029/2004GL021435, 2004.
- Davis, J.L., P. Elosegui, J.X. Mitrovica, M.E. Tamisiea, Climate-Driven Deformation of the Solid Earth from GRACE and GPS, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract G31C-0803, 2004.
- Elosegui, P., J.L. Davis, J.X. Mitrovica, M.E. Tamisiea, Estimating Geocenter Variations by Combining GRACE and GPS Data Sets, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract G34A-03, 2004.
- Cardellach, E., P. Elosegui, J.L. Davis, Towards improving the accuracy of GPS-based global vertical velocity estimates, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract G21BA-06, 2004.

4- Addendum: "Compilation of Published Estimates of Annual Geocenter Motions Using Space Geodesy"

Compilation of Published Estimates of Annual Geocenter Motions Using Space Geodesy

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Different authors have used different conventions to define annual geocenter motions. This document is an effort to compile existing estimates of annual geocenter motions and report them using a consistent definition.

1 Introduction

1.1 Geocenter Motions

The definition of the term "geocenter motion" depends on the adopted origin of the reference frame. Common reference frames used in Space Geodesy include: the center of mass of the whole Earth (CM), the center of mass of the Solid Earth without mass load (CE), and the center of figure of the outer surface of the Solid Earth (CF) (see e.g., *Dong et al.*, 2003).

There are two established definitions of the term geocenter: one, the vector offset of CF relative to CM and, two, the reverse, the vector offset of CM relative to CF (see e.g., *Bouillé et al.*, 2000; *Dong et al.*, 2003). Obviously, their amplitude is the same and their phase differs by 180°. Following *Dong et al.* [2003], we label the first X_{CF}^{CM} and the second X_{CM}^{CF} (i.e., the superscript represents the frame, the subscript represents any point in the frame).

1.2 Annual Motions

The two conventions commonly used to define annual motions are the "co-sine" with a "minus" phase and the "sine" with a "plus" phase. As for units, either mm or 10^{22} kg m have been used for amplitude, and either degrees or days for phase.

1.3 Annual Geocenter Motions Convention in El05

In this document, and in *Elosegui et al.* [2005] (El05), we will use the following convention: X_{CF}^{CM} for the geocenter, and $A \cos[2\pi\nu(t - t_o) - \phi]$ for annual motion, where A is amplitude, ν is annual frequency (1/365.25), t is the day of year, t_o is 1 January, and ϕ is phase. The units that we will use for reporting amplitude and phase are mm and degrees, respectively.

1.4 Published Annual Geocenter Motion Estimates

Table 1 and 2 summarize published estimates of annual geocenter motions and conversions to El05. The following sections are a review of those estimates.

Table 1: Phase conventions used in published annual geocenter motion estimates using Space Geodetic techniques

Reference	Code	Frame	Annual	Note
<i>Eanes</i>	Ea97			No phases reported
<i>Chen</i>	Ch99	CF	sinR	Inferred from Bo00 and Do00
<i>Argus</i>	Ar99	–	–	NA yet
<i>Bouillé</i>	Bo00	CF	cosT	Stated
<i>Blewitt</i>	Bl01	CF	cosR	Stated, with A in 10^{22} kg m
<i>Crétaux</i>	Cr02	CF	cosT	Inferred from Bo00
<i>Wu</i>	Wu03	CF	cosT	Stated
<i>Dong</i>	Do03	CM	sinR	Stated
<i>Elosegui</i>	El05	CF	cosR	Stated

where CF is X_{CM}^{CF} , CM is X_{CF}^{CM} , sinR is $A \sin[2\pi\nu(t - t_o) + \phi]$, cosR is $A \cos[2\pi\nu(t - t_o) - \phi]$, and cosT is $A \cos[2\pi\nu(t - t_o - \phi)]$ with ϕ in days relative to 1 January.

2 Satellite Laser Ranging (SLR)

2.1 *Eanes et al.* [1997] (Ea97)

This is a Fall AGU abstract. Estimates obtained using a 4-year time series of 12-day intervals of laser ranging data to Lageos-1 and 2 satellites. Only amplitudes reported in abstract. However, references to this publication by other authors also include phases. Cr02 says, as personal communication,

Table 2: Phase conversion to El05 annual geocenter motion convention

Reference	Factor	Note
Ea97		same solution as Ch99
Ch99	$90 - \phi$	sine to cosine
Bo00	$\phi \times 360/365.25$	days to degrees
Bl01	1	only amplitudes necessary
Cr02	$\phi \times 360/365.25$	days to degrees
Wu03	$\phi \times 360/365.25$	days to degrees
Do03	$90 - \phi + 180$	sine to cosine and CM to CF
El05	1	by definition

Amplitudes in Bl01 are degree-1 mass load, not displacement (see below for conversion to mm).

that the solution by Ch99 corresponds to a solution previously computed by Eanes, presumably as Ea97. Bo00 says something similar (Section 2.1), implying that Ea97 and Ch99 are equivalent.

Table 3: Reporting of Ea97 estimates

X		Y		Z		Reference
A	ϕ	A	ϕ	A	ϕ	
2.1		3.2		3.1		Ea97
2.2	59	3.2	299	2.8	45	Ch99
2.2	59	3.2	299	2.8	45	Bo00
2.2	59	3.2	299	2.8	45	Do03

Ch99 amplitude and phase values are from first entry in Table 1 of Ch99. That entry has Ea97 as reference. Bo00 and Do03 reference Ea97 for the values they quote, but they may come from Ch99.

2.2 *Chen et al. [1999] (Ch99)*

Estimates obtained using a 4-year time series of 12-day intervals of laser ranging data to Lageos-1 and 2 satellites. Approximate data span 1992.75–1997.25, after Plate 1. Presumably the same data set as Ea97.

Amplitude and phase values are in first entry in Table 1 of Ch99, and

Table 4: Reporting of Ch99 estimates

X		Y		Z		Reference
A	ϕ	A	ϕ	A	ϕ	
2.2 ± 3.5	59	3.2 ± 3.8	299	2.8 ± 8.6	45	Ch99
2.2	58	3.2	295	2.8	44	Cr02

plotted in Figure 3 as Lageos 1/2. (Figure 3c also shows an undocumented Lageos 1/2 (96/97) vector.) Amplitude uncertainties are from text in Section 2.4. No uncertainties available for phase estimates but will probably be large based on Plate 1, and last sentence in Section 2.4.

The table caption defines the phase as 0 degrees on 1 January, but does not indicate what convention was used. I would have inferred from Plate 1 and phase values in Table 1 that the annual motion is expressed using a cosine convention, i.e., $A \cos[\omega(t - t_o) - \phi]$, but everyone reporting Ch99 express it as sine.

Cr02 reporting of Ch99 phases are incorrect by the day to degree conversion factor. Note that this Ch99 solution and Bo00 and Do03 solutions of Ea97 in Table 3 are the same.

2.3 Bouillé et al. [2000] (Bo00)

Estimates using a 4-year (1993.0–1997.0) time series of monthly intervals of laser ranging data to Lageos-1 and 2 satellites. Similar data set to Ea97/Ch99.

Table 5: Reporting of Bo00 estimates

X		Y		Z		Reference
A	ϕ	A	ϕ	A	ϕ	
2.1 ± 0.5	47	2.0 ± 0.5	322	3.5 ± 1.5	42	Bo00
2.1	47	2.0	322	3.5	42	Cr02
2.1 ± 0.5	47	2.0 ± 0.5	322	3.5 ± 1.5	42	Wu03
2.1 ± 0.5	47	2.0 ± 0.5	322	3.5 ± 1.5	42	Do03

Bo00 reports amplitude uncertainties in the text (Section 2.1) but not in the table (Table 1). No phase uncertainties are reported anywhere. More-

over, Bo00 says that the Z amplitude is 3.4 mm in Section 2.1, 3.5 mm in Table 1. Cr02 says (Table 1) that Bo00 amplitude uncertainties were not communicated.

2.4 Crétau et al. [2002] (Cr02)

Estimates using a 7-year (1993–1999) time series of monthly intervals of laser ranging data to Lageos-1 and 2 satellites. This work is an extension of Bo00.

Table 6: Reporting of Cr02 estimates

X		Y		Z		Reference
A	ϕ	A	ϕ	A	ϕ	
2.6±0.5	32±7	2.5±0.1	305±4	3.3±1.0	35±10	Cr02

These estimates correspond to solution 4 in Table 5. No further referencing of this solution yet.

3 DORIS

3.1 Bouillé et al. [2000] (Bo00)

Estimates using a 5-year (1993–1997) time series of monthly intervals of DORIS data to Topex/Poseidon satellite plus 5-years of monthly estimates of DORIS data to Topex/Poseidon and SPOT 1 and 2 satellites (second row in Table 1 of Bo00). The second entry in Table 7 below is only the T/P solution (third row in Table 1 of Bo00). Bo00 believes that the first solution (i.e., only T/P) is better based on comparisons to their SLR solution. Uncertainties reported in text (Section 2.2).

Table 7: Reporting of Bo00 estimates

X		Y		Z		Reference
A	ϕ	A	ϕ	A	ϕ	
2.4±1.4	163	2.1±1.3	319	2.1±1.1	305	Bo00 (T/P + SPOT)
1.8	65	5.0	281	3.0	332	Bo00 (T/P only)
1.8	65	5.0	281	3.0	332	Do03 (T/P only)

3.2 Crétau et al. [2002] (Cr02)

Estimates using the SLR data above plus laser ranging and DORIS data to Topex/Poseidon satellite.

Table 8: Reporting of Cr02 estimates

X		Y		Z		Reference
A	ϕ	A	ϕ	A	ϕ	
1.1 ± 0.7	16 ± 4	3.7 ± 0.2	288 ± 3	3.0 ± 1.0	56 ± 7	Cr02

These estimates correspond to solution 1 in Table 5. No further referencing of this solution yet.

4 GPS

4.1 Blewitt et al. [2001] (Bl01)

Estimates using 5 years of weekly GPS data, acquired by 66 IGS stations. Amplitudes were reported in units of 10^{22} kg m. Do03 transformed from degree-one mass load to geocenter motion, in mm, using Equation (8). We adopt the Do03 amplitude values here.

Table 9: Reporting of Bl01 estimates

X		Y		Z		Reference
A	ϕ	A	ϕ	A	ϕ	
$-\pm-$	86 ± 3	$-\pm-$	345 ± 3	$-\pm-$	56 ± 1	Bl01
3.3 ± 0.3	86 ± 3	4.8 ± 0.3	345 ± 3	11.0 ± 0.2	56 ± 1	Do03

4.2 Wu et al. [2003] (Wu03)

Estimates using 2+ years of daily GPS data, acquired by 200 stations. No reference to these values yet.

Table 10: Reporting of Wu03 estimates

X		Y		Z		Reference
A	ϕ	A	ϕ	A	ϕ	
0.7 \pm 1.5	117 \pm 131	3.8 \pm 1.2	16 \pm 20	4.5 \pm 1.0	27 \pm 13	Wu03

The X phase uncertainty looks like a typo. More likely to be 13 or 11 instead.

4.3 *Dong et al. [2003] (Do03)*

Estimates using various station distributions, data spans, and approaches (network shift, degree-1 deformation). Solutions from Table 2 of Do03, using the same order. First three rows are from network-shift approach for various data spans; last two rows from degree-1 deformation approach. No clear which is the "best" solution. No reference to these values yet.

Table 11: Reporting of Do03 estimates

X		Y		Z	
A	ϕ	A	ϕ	A	ϕ
6.9 \pm 0.7	84 \pm 6	8.3 \pm 0.7	24 \pm 5	31.1 \pm 1.6	154 \pm 3
3.9 \pm 0.4	71 \pm 6	11.1 \pm 0.4	346 \pm 2	25.6 \pm 0.7	164 \pm 2
4.8 \pm 0.4	50 \pm 5	3.6 \pm 0.4	310 \pm 7	9.4 \pm 0.5	165 \pm 3
1.7 \pm 0.3	43 \pm 9	2.8 \pm 0.3	324 \pm 6	6.5 \pm 0.3	42 \pm 3
2.1 \pm 0.3	46 \pm 7	3.3 \pm 0.3	333 \pm 6	7.1 \pm 0.3	38 \pm 3

4.4 *Elosegui et al. [2005] (El05)*

Estimates combining GRACE and GPS annual motions, the latter comprising a global network of \sim 80 IGS sites.

Table 12: Reporting of El05 estimates

X		Y		Z	
A	ϕ	A	ϕ	A	ϕ
2.5 \pm 0.2	143 \pm 5	1.6 \pm 0.2	141 \pm 7	6.0 \pm 0.2	319 \pm 0

5 Summary of Annual Geocenter Motion Estimates

Table 13 and Figures 1–4 summarize the estimates of annual geocenter motion presented in the previous sections.

Table 13: Summary of annual geocenter motion estimates

Solution	X		Y		Z		Reference
	A	ϕ	A	ϕ	A	ϕ	
SLR	2.2	59	3.2	299	2.8	45	Ea97/Ch99
SLR	2.1 ± 0.5	47	2.0 ± 0.5	322	3.5 ± 1.5	42	Bo00
SLR	2.6 ± 0.5	32 ± 7	2.5 ± 0.1	305 ± 4	3.3 ± 1.0	35 ± 10	Cr02
DORIS	1.8	65	5.0	281	3.0	332	Bo00
DORIS	1.1 ± 0.7	16 ± 4	3.7 ± 0.2	288 ± 3	3.0 ± 1.0	56 ± 7	Cr02
GPS	3.3 ± 0.3	86 ± 3	4.8 ± 0.3	345 ± 3	11.0 ± 0.2	56 ± 1	Bl01
GPS	0.7 ± 1.5	117 ± 131	3.8 ± 1.2	16 ± 20	4.5 ± 1.0	27 ± 13	Wu03
GPS	2.1 ± 0.3	46 ± 7	3.3 ± 0.3	333 ± 6	7.1 ± 0.3	38 ± 3	Do03
GPS	2.5 ± 0.2	143 ± 5	1.6 ± 0.2	141 ± 7	6.0 ± 0.2	319 ± 0	El03

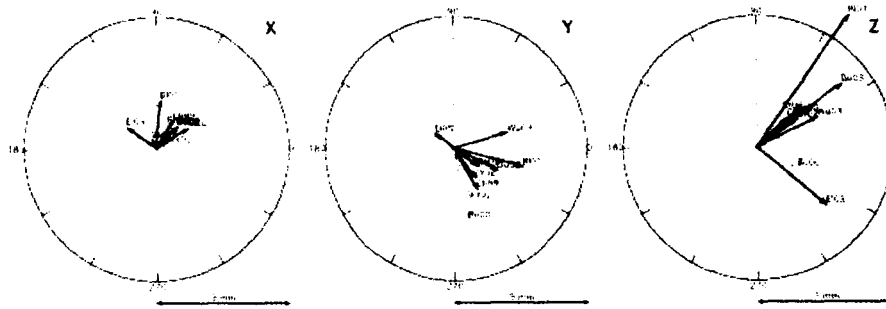


Figure 1: Summary of annual geocenter motion estimates from (blue) SLR, (green) DORIS, and (red) GPS.

References

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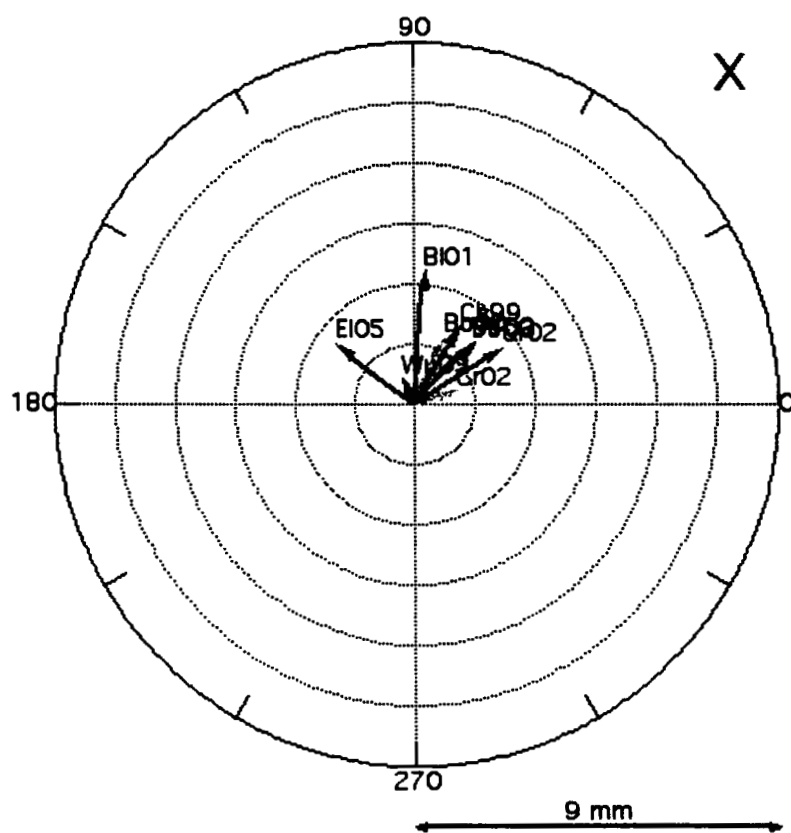


Figure 2: Annual geocenter motion X-component estimates from (blue) SLR, (green) DORIS, and (red) GPS.

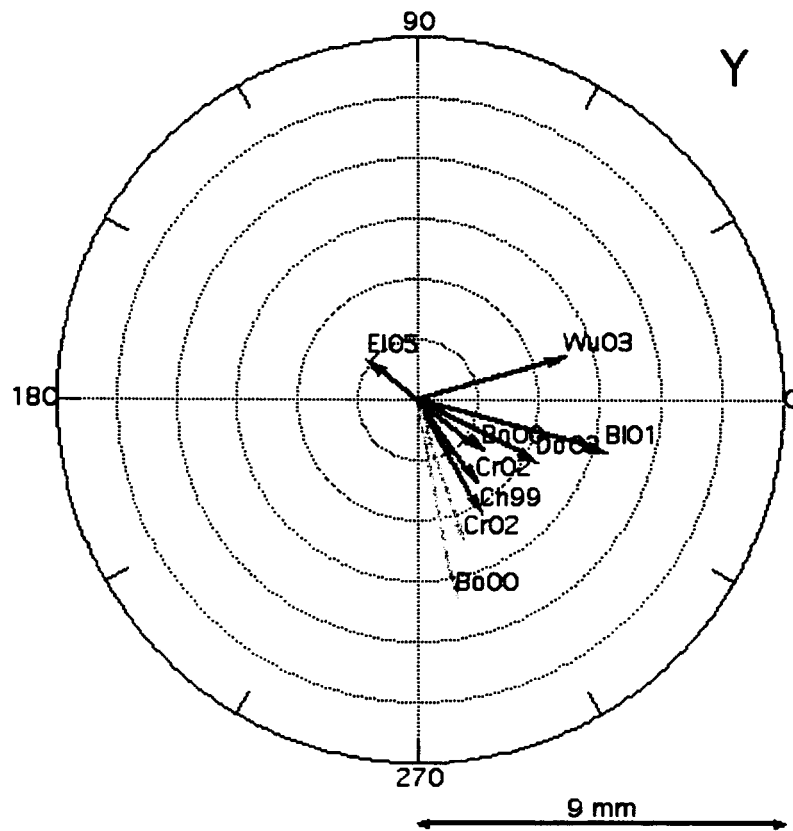


Figure 3: Annual geocenter motion Y-component estimates from (blue) SLR, (green) DORIS, and (red) GPS.

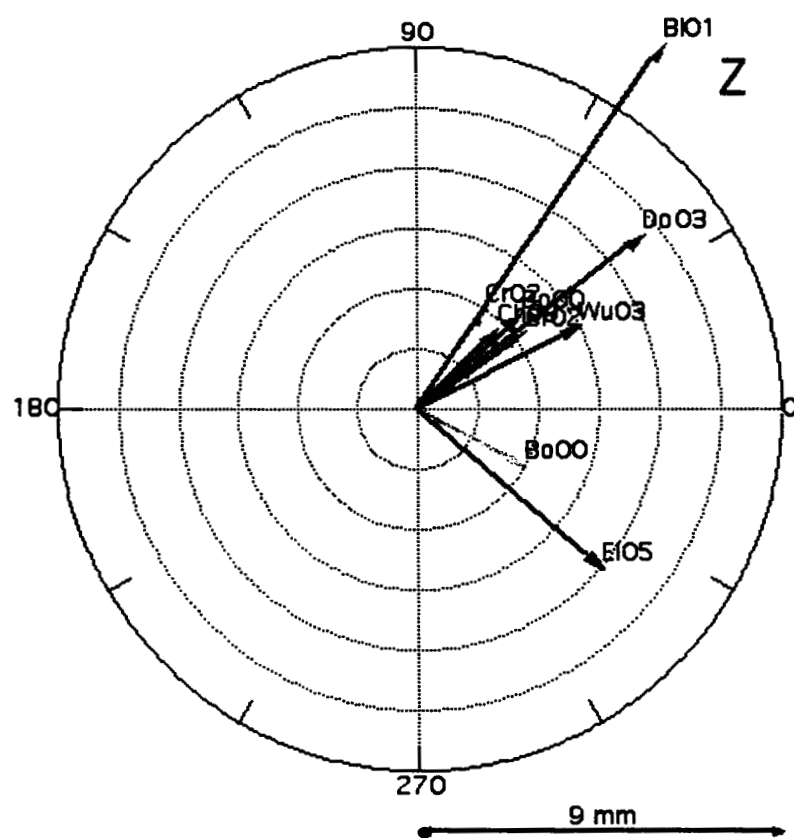


Figure 4: Annual geocenter motion Z-component estimates from (blue) SLR, (green) DORIS, and (red) GPS.